A search for VHE counterparts of galactic Fermi sources

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ABSTRACT. Very high-energy (VHE; E>100 GeV) gamma-rays have been detected from a wide range of astronomical objects, such as SNRs, pulsars and pulsar wind nebulae, AGN, gamma-ray binaries, molecular clouds, and possibly star-forming regions as well. At lower energies, sources detected using Large Area Telescope (LAT) aboard Fermi provide a rich set of data which can be used to study the behavior of cosmic accelerators in the GeV to TeV energy bands. In particular, the improved angular resolution in both bands compared to previous instruments significantly reduces source confusion and facilitates the identification of associated counterparts at lower energies. In this proceeding, a comprehensive search for VHE gamma-ray sources which are spatially coincident with Galactic Fermi/LAT bright sources is performed, and the GeV to TeV spectra of selected coincident sources are shown. It is found that LAT bright GeV sources are correlated to TeV sources, in contrast with previous studies using EGRET data.

1. Introduction

The knowledge of the very high-energy (VHE; E >100 GeV) sky has greatly improved during the last few years, thanks to the high sensitivity of current imaging atmospheric Cherenkov telescopes (IACTs), e.g. H.E.S.S., MAGIC, and VERITAS. At lower energies, observations using γ-ray satellites like *CGRO*/EGRET, *AGILE*, and *Fermi*/LAT represent the dominant efforts in the field of high-energy γ-ray astronomy.

Funk et al. (2008) compared γ-ray sources in the third EGRET catalogue (Hartman et al.(1999)) and those 22 then-published H.E.S.S. sources within the region of $l = -30^\circ$ to 30°, $b = -3^\circ$ to 3° (Aharonian et al.(2006)). They did not find spatial correlation between the two populations. However, due to the capabilities of the EGRET experiment, this study suffers from the following limitations: (1) The sensitivity of EGRET is relatively poor. The lack of photon statistics leads to poor-constrained spectral indices and the spectra end $\sim$10 GeV at the upper end for a typical source; (2) EGRET sources are only localized to degree-scales, which is much larger than the angular resolution of IACTs. These disadvantages are now largely improved by the better performance of LAT over EGRET.

In February 2009, the *Fermi*/LAT bright source list (BSL) was released (Abdo et al.(2009a)). In this work, VHE counterparts detected using IACTs of each source in this list are searched for based on spatial coincidence, and the GeV to TeV spectra of several selected coincident sources are depicted.

2. Search for spatial coincidence

2.1. The Fermi and VHE catalogues

Abdo et al. (2009a) present 205 point-like γ-ray sources detected in the $0.2 - 100$ GeV band based on three months of observations (August 4, 2008 – October 30, 2008). The authors assign for each source a source class, as well as γ-ray and lower energy association (if any). Those sources that are classified as extragalactic (all AGN and the Large Magellanic Cloud) are not considered below. Most of the LAT bright sources studied in this work are, therefore, of Galactic origin.

The remaining source list contains 83 sources, that consists of 15 radio/X-ray pulsars, 15 new pulsars discovered using LAT, 2 high-mass X-ray binaries (HMXBs), one globular

cluster (47 Tuc), 13 SNR/PWN candidates, and 37 sources without obvious counterparts at lower energy bands (Unids) (Abdo et al.(2009a)).

The number of VHE γ-ray sources is larger than 50 (Aharonian et al.(2008e); Chaves et al.(2009a); Chaves et al.(2009b)). The VHE γ-ray source positions and source extension in this work are taken from the corresponding publications. At higher energies, the Milagro collaboration reported evidence of multi-TeV emission from several LAT source positions (Abdo et al.(2009b)). Only those source candidates with significance larger than five are regarded as TeV sources here. With several tens of known sources in both the GeV and TeV bands, a systematic cross-correlation study is conducted.

2.2. Level of spatial coincidence

To quantify the level of spatial coincidence, the following scheme is employed. Let d be the distance between a LAT best-fit centroid position and a nearby VHE source centroid position. The radius of 95% confidence region for the LAT source is the uncertainty on the centroid position of the given LAT source, which is typically $\sim 0.1°$. Most VHE sources are extended, with a typical extension of $0.1° - 0.5°$. Let e be the sum of the radius of 95% confidence region and the source extension of the VHE source.

For each LAT source, if a VHE source was found where $d - e < 0$, the source pair is called a spatial coincidence case (i.e. category Y – Yes). Given a possible extended nature of many LAT bright sources, so that the sources seen by LAT and VHE instrument may actually overlap with each other, a category P (for Possible) is defined for pairs where $0 < d - e < 0.3°$. If no reported VHE source was found with $d - e < 0.3°$: the LAT source falls into the coincidence level N (for No coincidence with any VHE source). If there are several nearby VHE sources, only the closest VHE source would be considered.

2.3. Spatial coincidence GeV/TeV pairs

In the search, 23 coincident cases (Y, among them three are coincident with Milagro source only) and 5 possibly-coincident cases (P) are found. The results are presented in Tables I, II, and III. No reported VHE sources are found in the remaining 55 sources, as of October 2009.

The results are summarized as follows:

1. Six LAT pulsars are spatially coincident with a source detected using IACTs, which may be the VHE-emitting PWN. In addition, three other have a MILAGRO counterpart, and have not been reported as detected using any IACTs yet.
2. Among the 13 SNR/PWN candidates in the Fermi BSL, more than a half (7) are spatially-coincident with a VHE source, and additionally one being a possibly coincident case. The seemingly high fraction of coincidence is partly due to a better coverage of the inner Galaxy region with IACTs, where most SNR/PWN candidates are located.
3. The two high-mass X-ray binaries listed in the BSL (0FGL J0240.3+6113/LS I +61 303 and 0FGL J1826.3–1451/LS 5039) are both found spatially coincident with a VHE gamma-ray source, identified with the same corresponding binary.
4. Five out of the 37 unidentified 0FGL sources are spatially coincident with a VHE gamma-ray source. The number increases to nine if possible coincidence cases are included.

3. The gamma-ray spectral energy distributions

Assuming a single power law, F_{23} and F_{35}, photon flux in the low energy (10^2–10^3 MeV) and high energy (10^3–10^5 MeV) band, respectively (Abdo et al.(2009a)), are given by $F_{23} = k \int_{0.1}^{1} E^{-\Gamma} dE$ and $F_{35} = k \int_{1}^{100} E^{-\Gamma} dE$, where E is measured in GeV, Γ is the

TABLE I
0FGL sources with spatially coincident VHE counterpart. PSR: pulsars; SNR/PWN: supernova remnants/pulsar wind nebulae candidates; Unid: unidentified sources; HMXB: high-mass X-ray binaries.

LAT source	association	class	VHE source
0FGL J0534.6+2201	Crab	PSR	HESS J0534+220
0FGL J0835.4–4510	Vela	PSR	HESS J0835–455
0FGL J1418.8–6058		PSR	HESS J1418–609
0FGL J1709.7–4428	PSR B1706–44	PSR	HESS J1708–443
0FGL J1907.5+0602		PSR	HESS J1908+063
0FGL J2032.2+4122		PSR	TeV J2032+4130
0FGL J0617.4+2234		SNR/PWN	VER J0616.9+2230
0FGL J1615.6–5049		SNR/PWN	HESS J1616–508
0FGL J1648.1–4606		SNR/PWN	Westerlund 1 region
0FGL J1714.7–3827		SNR/PWN	HESS J1714–385
0FGL J1801.6–2327		SNR/PWN	HESS J1801–233
0FGL J1834.4–0841		SNR/PWN	HESS J1834–087
0FGL J1923.0+1411	W 51C	SNR	HESS J1923+141
0FGL J1024.0–5754		Unid	HESS J1023–575
0FGL J1805.3–2138		Unid	HESS J1804–216
0FGL J1839.0–0549		Unid	HESS J1841–055
0FGL J1844.1–0335		Unid	HESS J1843–033
0FGL J1848.6–0138		Unid	HESS J1848–018
0FGL J0240.3+6113	LS I +61 303	HMXB	VER J0240+612
0FGL J1826.3–1451	LS 5039	HMXB	HESS J1826–148

TABLE II
0FGL sources with coincident MILAGRO source only

LAT source	class	Milagro source
0FGL J0634.0+1745	PSR	MGRO C3
0FGL J2020.8+3649	PSR	MGRO J2019+37
0FGL J2229.0+6114	PSR	MGRO C4

photon index, and k is the normalization at 1 GeV. From these two expressions, k and Γ can be obtained. The spectra in form of "bowties" are then constructed. The power-law spectra are drawn from 100 MeV up to a certain maximum energy, $E_{\rm max}$ (<100 GeV), which is defined by requiring that the photon spectrum above $E_{\rm max}$ contains 10 photons over the three months of observations.

Examples of the MeV–GeV spectra of spatially coincident GeV/TeV sources are depicted in Figures 1 to 3. Figure 1 shows four EGRET pulsars and their TeV-emitting nebula. Figure 2 shows the MeV to TeV spectra of two coincident GeV/TeV sources (0FGL J1839.0-0549/HESS J1841-055 and 0FGL J1848.6-0138/HESS J1848-018) in which the γ-ray spectra may be described by a single spectral component. Figure 3 shows the MeV to TeV spectra of two coincident GeV/TeV sources (0FGL J1805.3-2138/HESS J1804-216 and 0FGL J1834.4-0841/HESS J1834-087) in which two spectral components may be needed to describe the γ-ray spectra. It should be stressed that this notion is useful only if power-law spectra are good descriptions of the 0.1–$\sim$100 GeV source spectra.

TABLE III
0FGL sources with possibly coincident VHE source

LAT source	class	VHE source
0FGL J1814.3–1739	SNR/PWN	HESS J1813–178
0FGL J1634.9–4737	Unid	HESS J1634–472
0FGL J1741.4–3046	Unid	HESS J1741–302
0FGL J1746.0–2900	Unid	HESS J1745–290
0FGL J1836.1–0727	Unid	HESS J1837–069

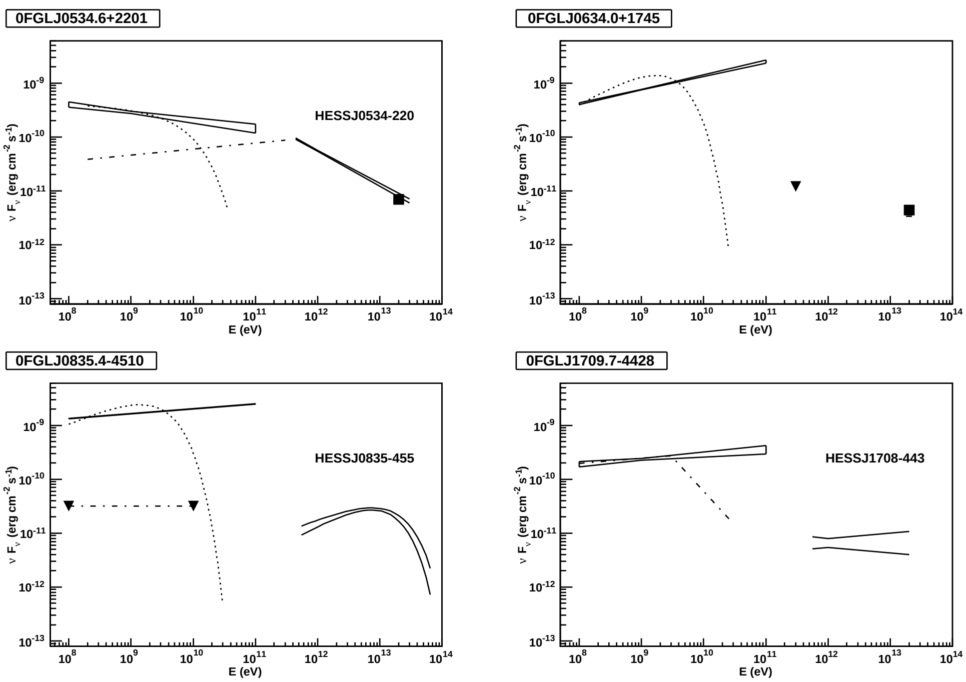

Fig. 1. Spectra of four EGRET pulsars and their TeV-emitting nebula. The solid lines at GeV energies represent the power-law representation described in Sect. 3.1. The "cut-off" GeV spectra up to several tens of GeV are the pulsed components, while the dashed-dotted lines in Crab (0FGL J0534.6+2201) and Vela (0FGL J0835.4–4510) are the nebula components (or upper limits thereof), both taken from the literatures.

4. The inner Galaxy region

Although VHE observations only cover a small part of the whole sky, they do cover the majority of the inner Galaxy region. In particular, the H.E.S.S. telescopes have surveyed the region of $l = -85°$ to $60°$, $b = -3°$ to $3°$ up to summer 2009 (Chaves et al.(2009b)). In this region, there are 41 *Fermi* bright sources. Among them, 16 are found coincident with a VHE counterpart. This fraction ($\sim$2/5) is higher than that for EGRET where about 1/4 of the EGRET sources (in a smaller region) are found to have a coincident VHE counterpart (Funk et al.(2008)). Moreover, the number raises to 21 if possibly coincident cases are included. LAT radii of 95% confidence region are mostly much smaller than EGRET error boxes, which further strengthens the case. A

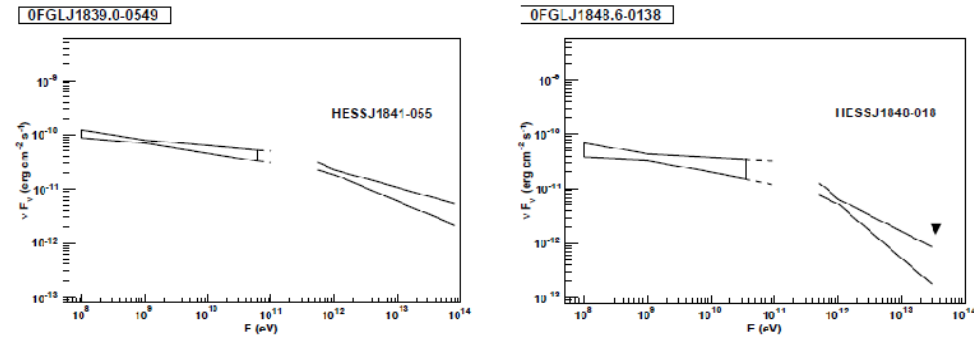

Fig. 2. MeV to TeV spectra of two coincident GeV/TeV sources in which the γ-ray spectra may be described by a single spectral component

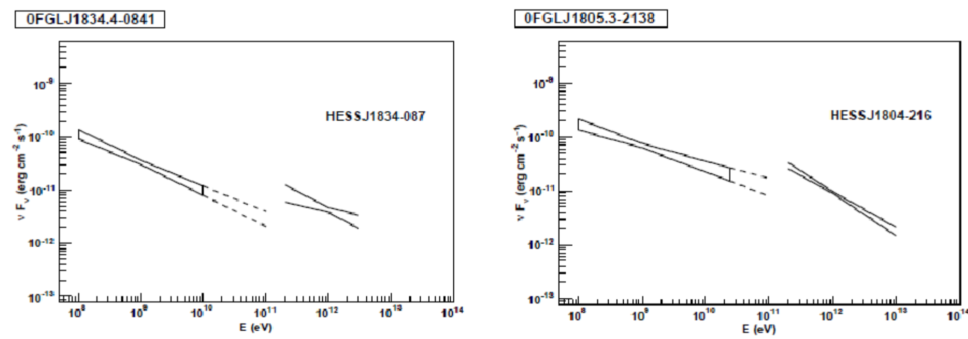

Fig. 3. MeV to TeV spectra of two coincident GeV/TeV sources in which two spectral components may be needed to describe the γ-ray spectra

breakdown of the number of coincidence cases for each source population in the region of $l = -85°$ to $60°$, $b = -3°$ to $3°$ is shown in Table IV.

5. Conclusion

This study, that largely benefits from the better angular resolution and better sensitivity of LAT over its predecessors including EGRET, for the first time, reveals a correlation between the GeV/TeV populations. The high fraction of *Fermi* bright sources spatially coincident with a VHE counterpart cannot be a chance coincidence. This means that there exists a common GeV/TeV source population. On the other hand, a single spectral component is unable to describe some sources detected in both GeV and TeV energies. Two spectral components may be needed in these sources to accommodate the spectral energy distribution in γ-rays.

References

Abdo, A. A., Ackermann, M., Ajello, M., et al. (Fermi/LAT Collaboration), 2009a, *Astrophys. J. Suppl.* **183**, 46

Abdo, A. A., Allen, B. T., Aune, T., et al. (MILAGRO Collaboration), 2009b, *Astrophys. J. Lett.* **700**, L127

TABLE IV
Number of coincidence cases for each source population excluding AGN in the region $l = -85°$ to $60°$, $b = -3°$ to $3°$. The numbers in brackets include possibly coincident cases (P).

LAT Source class	0FGL sources	spatially coincident cases
pulsars	10	4
SNR/PWN candidates	11	6 (7)
Unidentified sources	19	5 (9)
Total (including LS 5039)	41	16 (21)

Aharonian, F. A., Akhperjanian, A. G., Bazer-Bachi, A. R., et al. (H.E.S.S. Collaboration) 2006, *Astrophys. J.* **636**, 777
Aharonian, F., Buckley, J., Kifune, T., & Sinnis, G. 2008e, Reports on Progress in Physics **71**, 096901
Chaves, R. C. G., Renaud, M., Lemoine-Goumard, M., & Goret, P., for the H.E.S.S. Collaboration, 2009a, AIP Conference Proceedings **1085**, 219
Chaves, R. C. G., on behalf of the H.E.S.S. Collaboration, 2009b, “Extending the H.E.S.S. Galactic Plane Survey”, to be published in the proceedings of the 31st International Cosmic Ray Conference
Funk, S., Reimer, O., Torres, D. F., & Hinton, J. A. 2008, *Astrophys. J.* **679**, 1299
Hartman, R. C., Bertsch, D. L., Bloom, S. D., et al. 1999, *Astrophys. J. Suppl.* **123**, 79